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FEASIBILITY OF MINING LUNAR RESOURCES FOR EARTH USE:
CIRCA 2000 A. D.
VOLUME I: SUMMARY

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FOREWORD

This is probably the first pragmatic study examining the feasibility of obtaining lunar minerals for terrestrial utilization. Also, it is one of the first studies to evaluate lunar mining based on data obtained from the Apollo landings and lunar soil samples. Although our knowledge of the moon is still lacking, some encouraging results such as high aluminum and iron ore concentrations have been discovered in both returned soil samples and in the data obtained from the Apollo subsatellites. These results, combined with results from recent studies of terrestrial mining resources which warn of the imminent depletion of terrestrial mineral resources, have been the impetus behind this study.

Preliminary results early in the study gave indications that it will not be economically feasible to mine, refine, and bring the lunar minerals back to Earth for consumption. But the authors felt that the final results would be of general interest, and therefore the study was completed and documented. The results have consistently indicated, on the other hand, that the concept is technically sound.

The study is reported in two volumes. Volume I, the "Summary", presents a general overview of the study and covers primarily the results and conclusions for the study. Volume II, "Technical Discussion", reports how the study was done and includes the technical and economic analyses and the detailed results.

ACKNOWLEDGMENT

The authors of this study extend their appreciation to the proponents and critics of this study. They have both been helpful in making this a balanced study.

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ABSTRACT

The feasibility of commercially mining the moon for minerals destined for Earth use in the early 21st Century is reported here. The study was undertaken to determine whether it might be appropriate for NASA to include in its planning, development of space technology that would be pertinent to such an undertaking. Also, the question of depleting commercially exploitable Earth mineral resources in the 21st Century is becoming of national concern, and this concept appeared as though it could be a possible solution to this problem. The results show that, within the technological constraints of this study, it would not be commercially feasible to mine, refine, and bring back to Earth lunar minerals. Their costs are approximately two orders of magnitude higher than similar Earth mineral costs for the year 2000 A.D.

A broad systems approach was used to analyze and evaluate the problem. In the performance of the study, assumptions pertaining to the available transportation systems, equipment and science technologies were made to keep them consistent with that time period. This was necessary to obtain a realistic, representative cost for the lunar minerals. All major elements associated with the establishment of the mine and refinery facilities, the mining and refining operations, and the transport system for getting the mineral back to Earth have been included in the study.

INTRODUCTION AND BACKGROUND

From time to time, and more recently as the result of the rather dire predictions of the *Limits to Growth* (ref. 1) study sponsored by the Club of Rome, questions of the following general nature have been raised.

> Are visions of exploiting extraterrestrial sources of minerals for use on Earth nonsense or feasible dreams? Can the moon possibly be a source of minerals to supplement the Earth's finite supply? Is lunar mining an economically viable enterprise that can be undertaken within the next 50 years or so? Should NASA include in its long range planning the development of technologies pertinent to lunar mining on a commercial

scale and the technologies of related areas such as satellite survey and mineral detection on the moon?

A broad systems study seeking preliminary answers to these questions was undertaken within the Systems Studies Division and the results are reported here. The study has included all the general areas (transportation, base construction, mining, refining, power generation) that are expected to influence the final Earth delivered price of lunar minerals. The time setting of the study is the early 21st Century. Choice of the time period was based on our estimate of the earliest date when lunar mining could be technically feasible and is coincidental with the projected dates when shortage of certain strategic minerals is expected to be severe. In performing the study, the technologies connected with the establishment and operation of the facilities for obtaining lunar resources were assumed to be what would be available by the early 21st Century. These assumptions were a necessary part of the study to help assure that the lunar mineral cost projections would be realistic for that time period.

Returning to the problem of depletion of Earth resources, let us examine this question more fully and see how the consideration of lunar mining naturally follows. If the danger of depleting natural resources on Earth and the associated order of magnitude cost increases alluded to in the book entitled *Limits to Growth* (ref. 1) is correct, then the resultant economic crisis leaves only several options that the nations of Earth can choose.

1. Continue to use up the resources at an ever increasing rate and hope that a solution will manifest itself;
2. Try to slow down the rate of use of the resources by population control;
3. Start now to develop the technology and institute recycling of resources;
4. Legislate a per capita consumption quota for resources; or
5. Explore new sources where resources might be obtained.

Note that all options are viable, but the first four all have obvious

undesirable features, and all lead to eventual depletion. Only the fifth holds a hope (maybe faint) for providing the required resources; that is, supplement the dwindling Earth resources with an extraterrestrial source such as the moon. The feasibility of exploiting extraterrestrial sources, though still very speculative, has been shown to be possible at least on a preliminary basis by the United States Apollo program and the Russian Luna flights. However, the cost of obtaining lunar material using the Apollo system is rather high considering that on each flight less than 200 kilograms was brought back and the flight cost approximately $450 million. The Apollo samples indicate that the moon is rich in several useful metallic minerals (iron, aluminum, titanium, etc.). Also, Apollo 15 command module x-ray spectroscopy and data from the subsatellite launched by Apollo 16 indicated concentrated deposits of aluminum in the lunar highlands. Of course, these are only indications and the true picture of the lunar resources will not be known for some time to come.

Only one aspect of using lunar resources is investigated in this study--that of bringing the resources back for Earth use. A study (ref. 2) completed at the Johnson Space Center in Houston, Texas looks at the integration of lunar resources into the establishment and daily operation of a Lunar Colony. Many studies (refs. 3-9) examining the methodology of obtaining water, oxygen, and rocket propellants from the lunar soil were performed in the pre-1969 time period. Being done prior to the Apollo landings, they are probably of limited value. These studies largely neglected the economies of mining, and failed to treat the weight, refurbishment, cost, power, and size requirements for the required mining equipment. The only exception was the study by Shotts and Cox (ref. 3) which did include basic mining equipment based on terrestrial strip mining methods. They did not include the equipment required to process the lunar ore in their analysis. The transportation system picked for that endeavor was based on Saturn V technology and resulted in a lunar landed cost of $5,000 per pound--a prohibitive cost for a commercial undertaking requiring large payloads to be delivered to the moon.

Also during this 1960's time period, the Bureau of Mines, under contract to NASA, provided expertise in developing the mining equipment used on the moon by the Apollo astronauts such as the (coring) drill, as well as terrestrial simulations of the lunar terrain and soil on which the astronauts trained and tested their equipment. The flavor of these studies is covered in annual reports (such as refs. 5-9) issued by The Working Group on Extraterrestrial Resources and reports by the U.S. Department of Interior, Geological Survey, covering work done for NASA. (References 10-12 are examples of these reports.)

Based on the knowledge gained from these past efforts, we were able to isolate the more important issues. These issues are listed below.

1. What is the anticipated technology for terrestrial mining and refining for the early 21st Century?
2. Can terrestrial mining and refining technology be adapted for lunar use?
3. What are the power requirements?
4. What are the logistic requirements for sustaining the operation?
5. What are the transportation problems such as orbit phasing?
6. What are the costs associated with each of the above items?
7. Is mining and refining of lunar resources feasible?
8. Are there any anticipated scientific methods that can revolutionize mining and refining?
9. Do these make lunar mining feasible?

Of course, the answers to these questions are not precise but are rather our best estimates of the requirements of technology and economics. These estimates arrived at in this study are the results of systematic analysis of the operations and processes. Practical considerations of return on our effort and lack of reliable data necessitated neglecting several parameters and processes, but careful screening has assured that none of the important parameters and processes were neglected. Many assumptions were necessary in carrying on this study and the more important ones are identified below.

Assumptions

Any study set in the future has the problem of picking the appropriate technology and data consistent with that time period and proper balance of optimism and pessimism must be maintained. Therefore, in order to maintain such a balance, the study has chosen to include in the analysis a combination of known technologies and <u>foreseeable</u> breakthrough technologies. Also in carrying out the analysis, assumptions had to be made. A list of the more important assumptions made in the course of the study are listed below. Specific assumptions are further identified in the analysis.

1. Time setting is circa 2000 A.D.
2. Minable ores will be found on the moon.
3. Basic transportation system will exist.
   a. A second generation Earth orbital shuttle is available.
   b. Earth orbital space stations are in existence.
   c. Inter-orbit (Earth to lunar orbit and return) reusable nuclear shuttle has been developed.
   d. Lunar landing (lunar surface to orbit and return) reusable tug has been developed.
4. That currently existing robotic controls, automated computer controlled operations, and their like would be vastly improved in reliability and capability and become state-of-the-art by 2000 A.D.
5. Advanced technologies for systems such as fusion power, fusion torch, thermal borer, etc. would be developed and these systems available at least in basic form. But their consideration in this analysis would be limited for some by availability of data.
6. Equipment for base construction, mining, and refining can be modularized to fit in the shuttle cargo bay.
7. Ore content is 1 percent for computational convenience (see paragraph below for further explanation).
8. Costs are in 1972 dollars.
9. All weights stated in pounds are Earth pounds.
10. Operations are 24 hours a day, 365 days a year. Per man work week is less than 40 hours and a work shift is for eight hours.
11. The operation has been nominally sized for a production rate of 4.5×10^6 kilograms per year (10^7 pounds per year) of pure mineral.

Assumption 7 was made fully understanding that for most minerals it would be impossible to mine minerals of such low ore content profitably

by current and extrapolated (year 2000) Earth standards. The ore richness of lunar minerals, even with five Apollo (Apollo 11, 12, 14, 15, and 16) samples, still cannot be estimated with any certainty. The choice of 1 percent provides a convenient base that can then be used for selecting an ore richness for any particular ore that may be profitably mined. This can be done by taking the results in cost, power, energy, etc., per kilogram and dividing it by the new ore richness in percent. In algebraic form: $C_x = C_1 \div X$, where C_x is the cost, power, energy, etc., required for any ore richness of "x"; C_1 is the cost, power, energy, etc., estimated in this study per kilogram for the base 1.0 percent ore.

DESCRIPTION AND ANALYSIS OF OVERALL SYSTEM FOR OBTAINING LUNAR MINERALS

This section describes the overall system required to establish, develop, mine, refine, and transport lunar minerals back to Earth. For analytical convenience, the overall system was separated into the following six areas:

1. Earth to Moon Transportation System.
2. Construction of Lunar Mining, Refining, and Support Facilities.
3. Power Generation System.
4. Mineral Mining System.
5. Mineral Dressing and Refining System.
6. Lunar Surface Payload Launcher.

Gross costs for each of these areas are also included with the following technical discussion of the above areas.

A summary of the weights and costs associated with the above areas is shown in table 1. The numerical values shown in table 1 provide an indication of the gross weight and cost requirements for the establishment and operation of a lunar mineral mining and refining operation.

An artist's rendition depicting the overall lunar mining facility and operation is shown in figure 1.

TABLE 1. - WEIGHT AND COST SUMMARY* OF LUNAR MINING

	Weight, kg.	System Cost	Operational Cost
Transport Cost - Earth to Moon	--	--	\$550/kg.
Lunar Mining Base	1.7×10^6	\$1.1 $\times 10^9$	\$160 $\times 10^6$/yr.
Power Generation System	$10^6 - 10^8$	\$1.0 - 100 $\times 10^9$ -	\$0.02 - 0.03/kw-hr.
Mining System**	244×10^3	\$135 $\times 10^6$	\$250 $\times 10^6$/yr.
Mineral Dressing and Refining*** Systems	500×10^3	\$275 $\times 10^6$	\$125 $\times 10^6$/yr.
Lunar Payload Launcher Moon to Earth	$0.07 - 70 \times 10^6$	\$0.4 - 400 $\times 10^8$	--

* These are summary values and the text should be consulted for details such as effect of equipment lifetimes.

** Explosives requirements constitute the operational cost.

*** Weight and cost of refining equipment is not included.

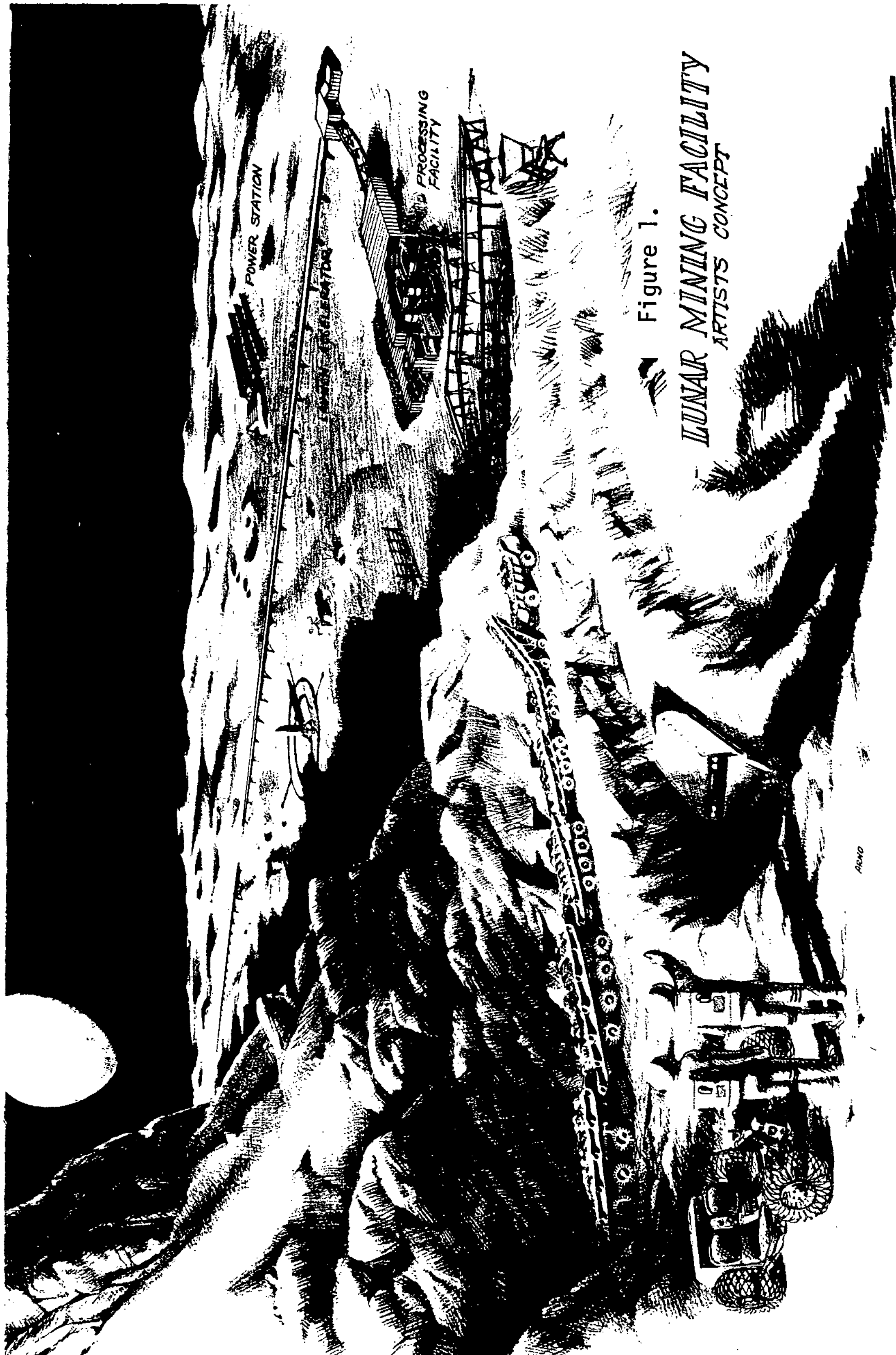

Figure 1.
LUNAR MINING FACILITY
ARTISTS CONCEPT

Earth to Moon Transportation System

The primary goal of the transportation system is to deliver payload from the Earth to the moon in the most economical manner while meeting the requirements of safety, flexibility, and efficiency.

A transportation system consistent with the early 21st Century time period was synthesized based on data from past studies (refs. 13-20) and evaluation of current technology trends in space systems. It is expected that second generation space shuttles will be available as will be reusable nuclear space shuttles and reusable chemical tugs. Assuming that these vehicles will be available, the transportation system was assembled in three parts. For the first part of the journey, from Earth surface to Earth orbit, the second generation space shuttle was assumed to be used. Its payload capability will be about 23,000 kilograms and the cost of orbiting this payload was assumed to be $25 per kilogram. For the second, or middle, portion of the journey a reusable nuclear space shuttle was assumed to be used. Initial screening of past studies (refs. 19, 20) showed that for these types of vehicles a payload of about 136,000 kilograms provides the most economical payload size to get from Earth orbit to Lunar orbit. The incremental cost for this part of the trip was determined to be $125 per kilogram including fuel as well as amortization costs. The final portion of the trip is accomplished by using a chemical tug. A chemical (LOX-LH_2) tug was chosen to eliminate the hazard of contaminating the lurain with radiation. The cost increment for this final part of the trip will be about $375 per kilogram including fuel and hardware. Thus the cost per kilogram of payload landed on the moon totals approximately $525; this was rounded to $550 for other computations in this study.

Some of the pertinent characteristics for the transportation system are summarized in table 2.

TABLE 2. - TRANSPORTATION SYSTEM CHARACTERISTICS

Characteristic	2nd Generation Space Shuttle	Interorbit Nuclear Shuttle	Lunar Tug
Operational Regime	Earth Surface to Earth Orbit	Earth Orbit to Lunar Orbit	Lunar Orbit to Lunar Surface
Velocity Req. (MPS)	9,140	4,240	2,190
No. of Reuses	100	10	10
Gross Weight* (kg)	--	433,000	69,000
Payload Capability (kg)	23,000	136,000	23,000
Payload Delivery** Cost ($/kg)	25	125	375

* Includes payload

** Total cost of a kilogram of payload delivered on the lunar surface is $525 but was rounded to $550 for other calculations in the study.

The transportation system does have a direct and significant effect on the cost of the mining and refining operations on the moon. The transport cost adds directly to the cost of all materials, equipment, etc. that are needed for establishing the mining and refining operations on the moon. In turn, the cost of the facilities as it is amortized will affect the price of refined minerals. Because of the direct impact that transportation has on the cost of the lunar facilities, we have tried in synthesizing the transportation system to be realistic; e.g., the number of reuses assumed for the second generation space shuttle was 100, well knowing that even the first generation shuttle is assumed to have a life of 100 reuses.

Construction of Lunar Mining, Refining and Support Facilities

The facilities required to house the mining and refining operations must be designed to provide a safe and comfortable environment for the workers in the most economical manner. Workers and equipment will require

protection primarily from radiation (solar and galactic), meteoroids, temperature fluctuations, and vacuum. Bremsstrahlung radiation from the galactic radiation (particles) must also be considered.

The lunar soil provides an excellent medium for protecting the facilities from the above environmental extremes. Therefore the base facilities have been configured to take advantage of this property. The protective thickness requirements are summarized in table 3. The depth of cover used will depend on whether the section of facility is manned or unmanned. Manned portions require protection from all three of the environmental elements listed in table 3 and thus will have a cover of lunar soil of at least five meters. Unmanned portions of the facilities require protection only from the temperature fluctuations and meteoroids; therefore a cover of one meter will be adequate.

TABLE 3. - LUNAR SOIL PROTECTIVE THICKNESS REQUIREMENTS

Environment	Lunar Soil Thickness Required, m	Remarks
Temperature Fluctuation: 90°K-390°K	0.1	With Cover ±3° C
Meteoroids	1.0	Survival Probability 0.995 (10 yr. & 1.0 km^2)
Radiation Solar & Galactic	5.0	Equivalent Protection to Earth's Atmosphere and Magnetic Field

An artist's rendering of the overall base was shown in figure 1 and the floor plan for the facilities is shown in figure 2. The anticipated construction method is to build an outer structural shell enclosing the entire volume including the floor. This shell will be capable of retaining a pressurized environment if required. The whole building will use

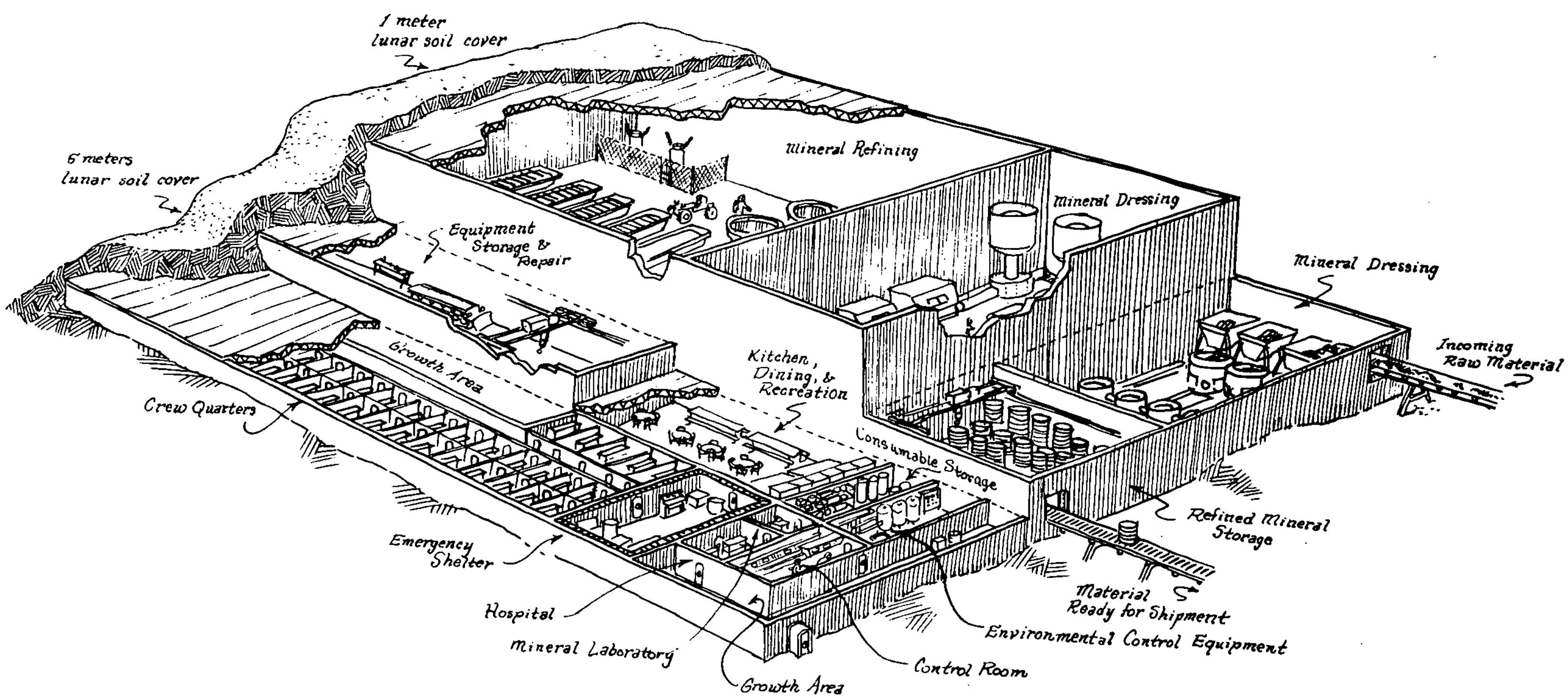

Figure 2. Facilities Floor Plan.

prefabricated construction for ease of assembly on the moon. In addition, each of the functional areas (e.g. laboratory, emergency, etc.) of the manned portions of the facilities will each be equipped with its own life support capability and also will be capable of normally working off the central life support system. Thus, together with the emergency section (module), a triple redundancy in life support is provided for the facility. The manned and unmanned sections of the facilities are identifiable in figure 2. The manned, and therefore normally pressurized, section of the base facility lies to the left of the central wall. A total volume of approximately 120,000 cubic meters is required for the facilities. Of this total volume, 15,000 cubic meters is manned and thus is pressurized with an atmosphere.

Figure 3 shows the arrangement of the base schematically, and gross dimensions are stated to provide the reader with an indication of the physical size of the base.

Total weight of the facilities including buildings, mining and refining (including mineral dressing) equipment and controls, and all crew requirements to make this an operational base is estimated to be approximately 2.5 million kilograms. Weights for the mining, mineral dressing and refining operations are discussed later in more detail.

Total assembled cost for the above facility is estimated to be $1.52 billion. Of this, the transportation cost amounts to $1.4 billion. The procurement cost on Earth for the overall facility is estimated to be $120 million. The erection cost for the base would be minimal, largely due to prefabriaction and modularizing of the facilities and equipment.

Facilities Operational Cost. - The operational costs covered here include only the logistic requirements pertaining to the crew needs and the leakage losses. The total operational cost for the facility should ordinarily include wear replacement and other items, such as explosives used for breaking rocks during mining. But it is more appropriate to

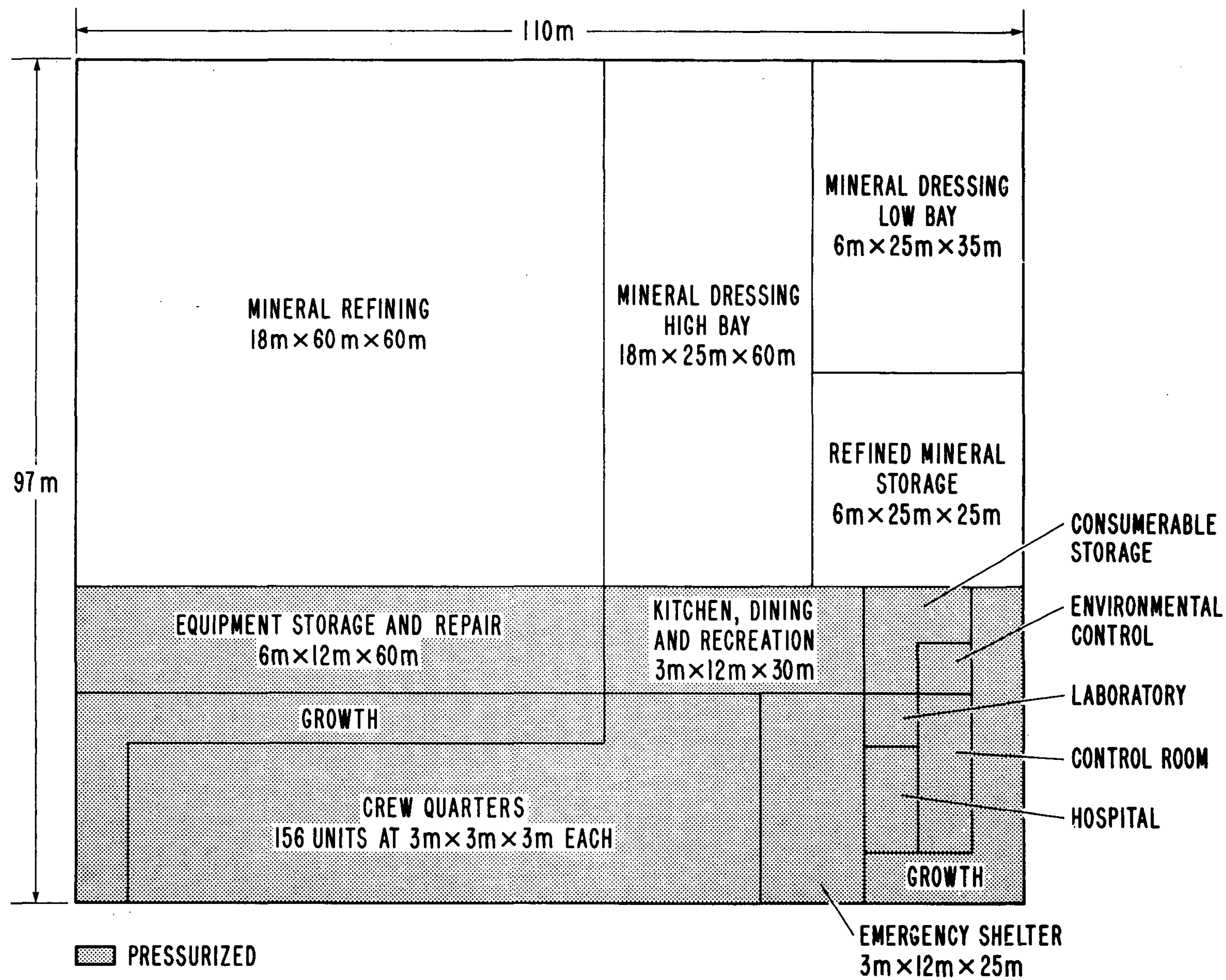

Figure 3. Facilities Layout and Dimensions.

include these costs under their own respective areas of mining, refining, power generation, or transportation.

The lunar base operating crew logistic requirements for consumables* are on the order of 4.5 kilograms (10 pounds) per man-day, assuming that water and oxygen are recycled (based on the Skylab and space station design studies). With this assumption, the yearly requirements for the base crew** of 150 men will be 270,000 kilograms (600,000 lbs) assuming a 10 percent allowance for spoilage and loss. The make-up requirements for atmospheric leakages through walls, air locks, and atmospheric regeneration equipment is estimated as approximately 18,000 kilograms (40,000 pounds) per year.

Total crew consumables and base leakage losses requirements are, therefore, on the order of 290,000 kilograms (640,000 pounds) per year and the cost to supply these needs will be \$160 x 10^6 per year.

Power Generation System

Availability of adequate power at a reasonable cost will be a key factor in such an energy intensive operation as mining and refining of lunar minerals. The forms in which the required energy can be supplied are many. Unfortunately the moon lacks any readily usable form of native energy with the exception of solar radiation. Therefore the energy needed to power the operation must be supplied from Earth, or if solar energy is utilized, the means of harnessing the solar radiation energy must be supplied from Earth.

Transportation cost from the Earth to the moon, even in the early 21st Century, will still be expensive and thus the energy supplied should be in a very concentrated form. Currently, nuclear fission or fusion are

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* Drinking water, personal hygiene water, oxygen, and food.

** See Volume 2 for occupational breakdown. Manpower needs were estimated from data contained in references 44 and 45 in Volume 2 and our best judgment.

two likely candidates. Solar energy, though not in concentrated form, was also considered here primarily because of its availability. These three candidate systems are discussed below. These systems are conservatively oversized to generate 10^6 kilowatts.

Solar Cells. - Solar cells have been widely used for converting solar energy to electrical energy in spacecrafts and currently have a conversion efficiency as high as 15 percent, but with future improvements this efficiency should rise to at least 20 percent. Continuous power requirements dictate that some energy storage system such as batteries or regenerative fuel cells be used in conjunction with solar cells for lunar night operation. Twelve million square meters of solar cells will be required and will weigh approximately 2×10^7 kilograms, while the accompanying regenerative fuel cells will weigh on the order of 10^8 kilograms. The cost for the system landed on the moon will be roughly \$50-\$100 billion. Of this cost, the equipment cost is optimistically estimated at \$10 billion and the rest of the \$100 billion cost is for transportation.

Nuclear Fission. - Power from nuclear fission is becoming a trusted state-of-the-art source for terrestrial applications and is in the experimental phase for space applications. The primary differences between the terrestrial and projected space applications of nuclear fission power is one of size (terrestrial sources are orders of magnitude larger), closed versus open cycles (space requires a closed system), and efficiency (terrestrial units are typically 3 to 6 times more efficient). Because of the need for a large amount of power at minimum cost and closed cycle operation on the moon, the unit designed for lunar use will probably incorporate features from both the terrestrial and space systems of today. Based on a power generation requirement of 10^6 kilowatts, a closed cycle nuclear fission power generation station for the moon complete with accessories will weigh approximately 10^8 kilograms and cost somewhat less than \$100 billion delivered on the moon. Equipment cost on Earth will be about \$10 billion and the transportation cost makes up the remainder of the \$100 billion total cost.

Nuclear Fusion. - The third power generation alternative, nuclear fusion, is probably the most desirable, but also the most speculative. Fusion has the potential of providing almost limitless power and can be the source of extremely high temperature plasmas useful to mining and refining operations. Current status for controlled nuclear fusion is one of rapid gains in technology with concept demonstration expected within the next ten years. Because of the more advanced technical basis of engineering today versus that when fission was demonstrated, the elapsed time between concept demonstration to commercial use of nuclear fusion would probably be shorter than the 20 odd years it took for nuclear fission. Currently, the projected theoretical efficiency for a direct conversion nuclear fusion power generating facility is estimated to be about 90 percent. But if the fusion power generating facility were to use a conventional thermodynamic cycle, the efficiency is expected to be about 45 percent. If the conventional thermodynamic cycle concept is used to generate the required one gigawatt electricity on the moon, the weight of the power station is estimated to be about 10^7 kilograms. The cost will be about $0.5 billion for the equipment and $6 billion for the transportation cost.

Power System Cost Discussion. - Since the energy requirements are more realistically on the order of 20 to 200 kilowatt-hours per kilogram of refined mineral, the range in power required for the nominal mineral production rate of 4.5×10^6 kilograms per year is 10^4-10^5 kilowatts. The power generation capacity was oversized (10^6 kilowatts) to allow for surges in power requirements during equipment start-up and electromagnetic accelerator use. The accompanying total cost for the power generation station will range from about $650 million to $10 billion. If a lifetime of thirty years is assumed, the per year amortization cost will be on the order of $20 million to $0.3 billion. This result can then be transformed to cost per kilowatt-hour by multiplying the generating capacity and hours per year then dividing the amortization cost by the product.

Operating costs for the power generation station will not likely be much higher than those for terrestrial stations. The largest unknown factor is the amount of servicing that will be required for the radiators (such as

keeping the radiating surfaces clean and repairing meteoroid damages). The operating costs are not expected to exceed two to three cents per kilowatt-hour. Therefore, the cost of electrical energy should be in the range of \$0.10 to \$1.00 per kilowatt-hour.

Mining System

The mining system includes all the processes from breaking of the ore, loading of the ore onto conveyors and conveying of the ore to the refinery. Also included are all necessary equipment to carry on those processes such as drilling, conveying, loading, etc.

Mining requirements on the moon are very different from terrestrial mining requirements due to the environmental differences between locations. Thus, direct transfer of terrestrial mining methods to the moon would not be possible. Some of the environmental differences will be of aid and others of hindrance. Examples of those environmental conditions aiding lunar mining are lower gravity which should decrease equipment wear and reduce roof falls (basic rock strength should not change), no water in mines, absence of noxious or explosive gases, and lack of native atmosphere to preclude spontaneous dust explosions. On the other hand, examples of environmental differences that may hinder lunar mining are the lack of a native atmosphere, making operational maintenance of equipment and machines very difficult; the extreme cold and high temperatures from lunar night (and shade) to day introduce thermal stress and lubrication problems; and the lack of water creates cooling, washing, flushing, and waste disposal problems.

A review of current terrestrial mining technology brought to light two important factors. First, mining technology has not been dynamic nor especially innovative over the years. It has rather been characterized by the adaptive use of engineering gains in other industries to increase the efficiency and capacities of the basic methodologies (concepts). Second, the processes and equipment used for mining are dependent on the mineral deposit being worked. These factors led us to conclude that future

mining concepts would most likely continue to be evolutionary rather than result from quantum changes. Therefore a remotely controlled mining machine was configured for this study as the most likely estimate of the future evolution of current mining machines.

Several concepts which may be more suitable for lunar use but not expected to be developed for terrestrial mining use are discussed later on in this section.

Figure 4 shows a sketch of the remotely controlled mining machine configured for this study. This machine will be electrically powered and capable of drilling holes for the explosives, placing the explosives, detonating the explosives, shielding itself from the explosion, scoop loading the broken ore onto its overhead conveyor, and in the event of roof falls, digging itself out. The machine and its accessory conveyors will be controlled via three dimensional television and cable hook-up from the base control room (see figures 2 and 3). The machine has been sized to handle 1.5×10^8 kilograms per year of material (ore) operating 50 percent of the time. Thus three machines are required to produce 4.5×10^6 kilograms of pure mineral per year from 1 percent ore. Gross dimensions for the machine are 2.4 meters high by 3 meters wide by 9 meters long. It is expected to weigh around 18,000 kilograms.

There are many systems that can be used to transport the mineral ore from the mining machine to the refinery. These systems can range from rail cars to conveyors and even to tired or crawler tread mobile trucks. The conveyor system was chosen for this study because of its relative simplicity and versatility to accommodate changes in length and ease of packaging for shipment. Versatility is achieved by designing a standard length conveyor and using as many of them as required to obtain the desired length. A nominal total conveyor length of 3000 meters was estimated as adequate based on terrestrial mine requirements. A conveyor of this length has a gross load capacity of 4.5×10^9 kilograms per year, weighs 1.9×10^5 kilograms and costs $105 million delivered on the moon.

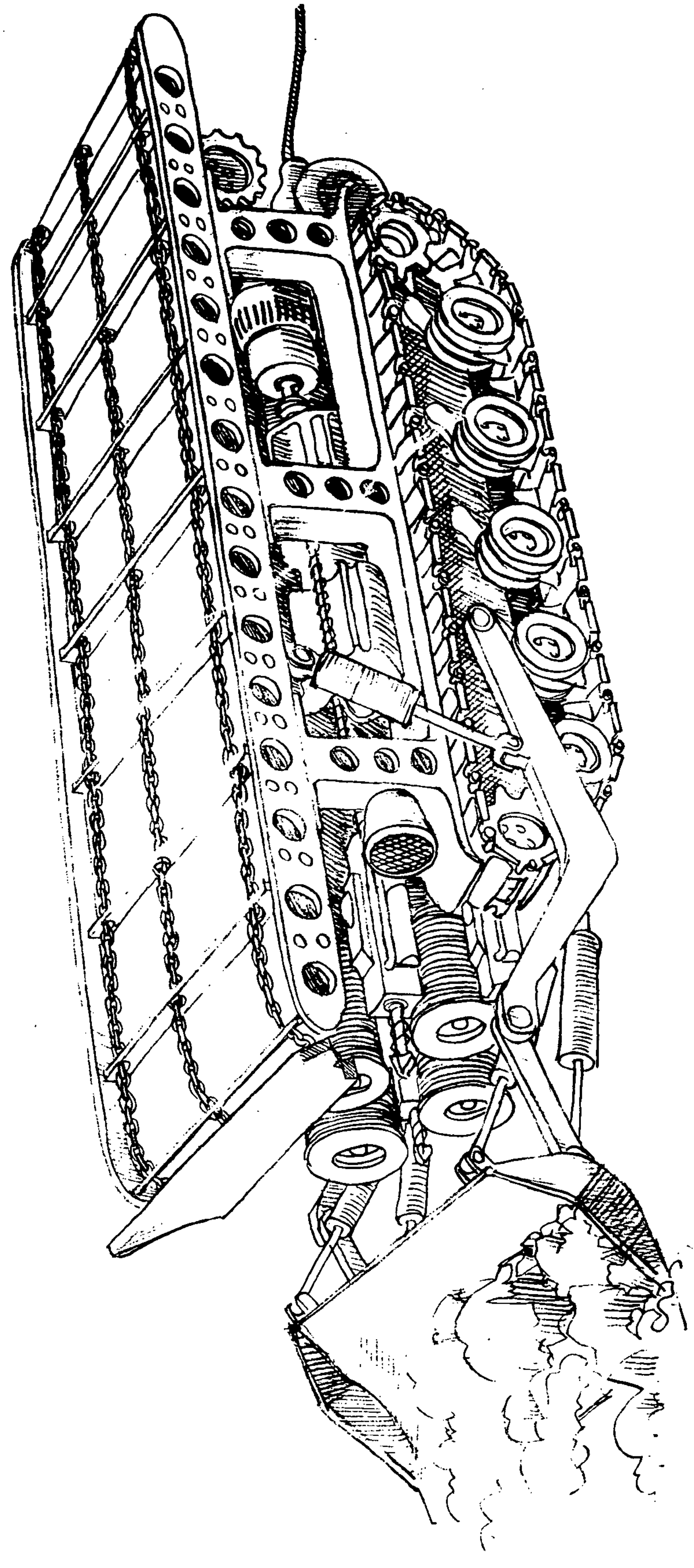

Figure 4. Automatic Lunar Miner.

Explosives generally have a yield of 1000 times their own weight in material moved. Thus for the base production rate of 4.5×10^8 kilograms per year of 1 percent mineral ore, 4.5×10^5 kilograms of explosives are required.

The total mining costs and power requirements are summarized in table 4.

TABLE 4. GROSS MINING POWER AND COST[(a)]

Equipment	Power Requirement KWH/yr	Power[(b)] Cost $/yr	Equipment[(c)] Cost $/yr	Total Cost $/yr
Mining Machines	2.6×10^6	2.6×10^5	6×10^6	6×10^6
Conveyor	2×10^5	2×10^4	21×10^6	21×10^6
Explosives	-	-	250×10^6	250×10^6
TOTALS	2.8×10^6	0.28×10^6	277×10^6	277×10^6

(a) Based on 4.5×10^8 kilograms per year of 1 percent mineral ore mined.

(b) Based on power cost of $.10 per kwh.

(c) Equipment amortization cost, based on a five year replacement cycle.

Procurement cost of the mining machine and conveyor is expected to vary between $2 and $20 per kilogram of equipment weight. As seen, the equipment costs are overwhelmed by the $550 per kilogram transportation cost and may therefore be neglected. One of the most important factors here is the high cost of the explosives. Some form of high yield explosives will be helpful in reducing this cost. Other mining methods not using explosives would alleviate this problem. A few potential concepts are discussed briefly in the following paragraphs.

New Concepts. - Included in these new concepts are the thermal borer, dielectric/laser rock breakage, water cannon rock breakage, and electrolytic furnace/fusion torch. Not enough information is currently available to

predict the future potential of these concepts with certainty; therefore they are only described briefly here.

Thermal Borer: The thermal borer is a concept which has been developed and tested successfully on a small scale by the Los Alamos Scientific Laboratory. It is a thermal device shaped like a bullet that bores into the rock by melting the rock and forcing the melted rock into voids in the surrounding rocks leaving a tunnel with smooth glasslike walls. Possibly nuclear power could be used to drive large sized thermal borers and melt the ore in situ. The molton ore could then be fed into an electrolytic separator where the desired mineral is separated from the gangue. Separation by the electrolytic separator is achieved by the application of an electric field.

Dielectric/Laser: Research in this area is being conducted by the U.S. Bureau of Mines and others. The dielectric process induces thermal stresses in the rocks by non-uniform heating or through localized restraint of the rock from thermal expansion. Generally in this process the rock is drilled and electrodes placed in the holes and high frequency alternating current fed into the rocks through the electrodes causing subsequent heating and fracture. Laser beams could be used to drill the required holes for the electrodes (conventional drilling is a costly operation). Unfortunately, efficiencies of lasers are currently too low, but rapid increases in efficiency are anticipated in the near future.

Water Cannon: This concept uses an extremely high pressure ($2 \times 10^9 - 7 \times 10^9$ n/m^2) water jet to fracture the rock. Some work in this area has been sponsored by the Department of Transportation in this country, but the Russians are world leaders in this technology. Water requirements are about one kilogram for every 27 kilograms of ore fractured--not very attractive for lunar use unless some means of totally recovering the water is found. If a substitute fluid such as molten silica could be used, the concept could become attractive, but this is still too speculative to consider seriously.

On-site Electrolytic Furnace/Fusion Torch: This concept could possibly be the most cost-effective and practical of all these new concepts but is still unproven. Controlled fusion is still to be achieved on a practical scale. Yet if the fusion torch becomes available the mining and reducing of lunar minerals to pure metals could be readily accomplished. The fusion torch will be used to melt the ore and the molten ore would then be electrochemically separated into various metals by utilizing the differential electrochemical potential of the metals. The fusion torch concept to melt and refine the ore is covered in the discussion on mineral refining.

Much basic research and development are required for this concept and the three preceding concepts. Serious consideration of these concepts will have to await results from research in those fields.

Mining System Cost Sensitivity. - Sensitivity of the mining cost with variation in percent ore richness is shown in table 5. Note the rapid decline in cost with increasing ore richness. The ore content for terrestrial mining varies widely depending on mineral; for example, the average grade of copper ore is 0.75 percent (ref. 21) while bauxite ore with an aluminum ore content of 50 percent (ref. 22) (equivalent to 26.5 percent aluminum metal in the bauxite ore) is considered average. The Apollo soil samples show average aluminum content of 7.5 percent which is comparable to the 8 percent for the Earth's crust. Data indicating concentrations of aluminum and iron have been obtained from the latest Apollo flights and the Apollo-launched subsatellites.

TABLE 5. - MINING COST FOR MINERAL PRODUCTION RATE - 4.5×10^6 kg/yr.

Percent Mineral Content	Production Cost Per Kilogram of Pure Mineral
1	\$60
25	\$ 2.40
50	\$ 1.20
75	\$ 0.80
100	\$ 0.60

Mineral Dressing and Refining

Once the ore leaves the mine and arrives at the refinery site, it will go through preparation and concentration phases, then finally go through a refining process where the mineral ore is reduced to the basic mineral. The preparation and concentration processes are collectively called "mineral dressing". The equipment and energy requirements and the costs associated with the mineral dressing operation are summarized below. For the refining operation only energy requirements and energy costs are summarized because details for determining the refining equipment costs are currently lacking. An explanation of these difficulties is included in the discussion of the refining operation.

Differences in the operating environment between the Earth and the moon introduce some unique problems in trying to synthesize the mineral dressing and refining operations on the moon. As with the other areas already discussed, the environmental differences make the direct transfer of terrestrial technology infeasible. Those environmental differences of prime concern to mineral dressing and refining operations are the lack of native air, water and hydrocarbons (coke, coal, etc.). Abundant (cheap) availability of these components is essential in terrestrial mineral dressing and refining operations. The lunar operations for mineral dressing and refining must be synthesized to avoid these needs.

Mineral Dressing. - The mineral dressing process can be divided into five general process steps as outlined in figure 5. Beside each of the five steps is shown a partial list of equipment or machine that may be used for terrestrial mineral dressing.

A hypothetical mineral dressing operation for processing lunar ore was assumed to consist of three stages crushing and two stages grinding with screening after each stage. Classification was by further screening and concentration was accomplished by magnetic or electrostatic separation.

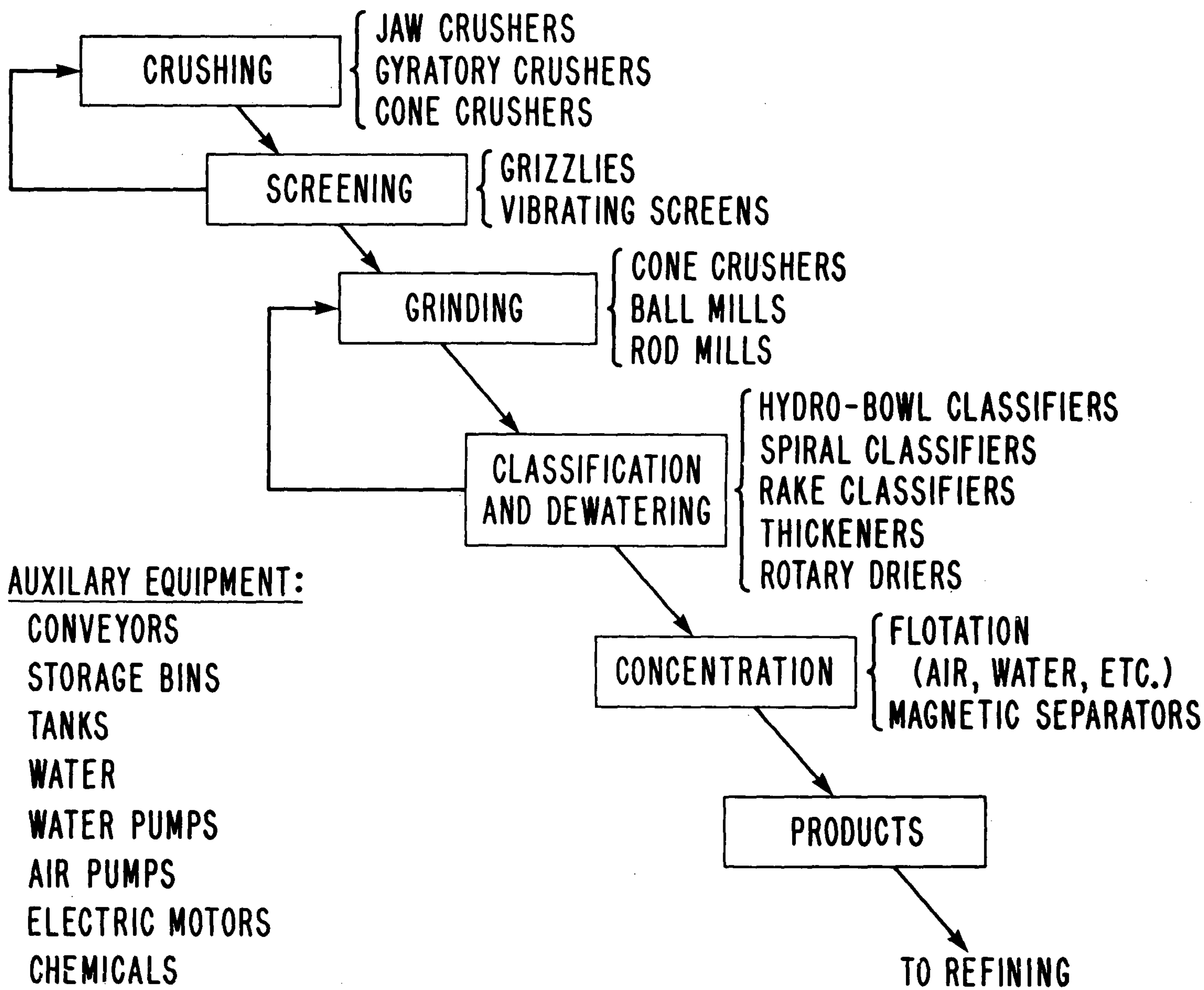

Figure 5. Terrestrial Mineral Dressing.

Weight, power, and cost estimates for the hypothetical mineral dressing operation were made for a nominal refined mineral production rate of 4.5 x 10^6 kilograms per year from 1 percent mineral ore. Total equipment weight is about 500,000 kilograms and this equipment delivered on the moon will cost $280 million. A problem of primary concern in the mineral dressing operation is wear in those parts of the equipment which come in contact with the ore. In particular, the crusher jaws, the screens, and the grinding balls and rods wear rapidly. The wear is on the order of one kilogram of equipment per 10^3 kilograms of ore.

Operational cost per year is expected to be around $120 million for replacement of worn equipment parts and $1 million for power (electricity). Lifetimes for the basic mineral dressing equipment are assumed to be ten years. Thus the total one year cost of the mineral dressing operation including amortization cost of the basic equipment is about $150 million.

The high wear replacement of equipment may be partially alleviated by using new concepts now in the embryonic phase. Examples are exposing rocks to laser beam to degrade their cohesive strength for easy crushing, or the heating and exposure to cryogenic temperatures to let the rock's internal stresses cause their own fracture. Feasibility evaluations for these concepts will require concept testing and experimental data.

Refining. - Few changes have occurred in basic refining methods, as illustrated for iron ore in figure 6. Review of the literature indicates that rapid changes in refining technology will probably not occur, although environmental protection legislation may force the industry into some drastic changes. None of the current terrestrial ore refining methods appear feasible for use on the moon for refining lunar ores. The logistic requirement for supplying the required chemicals, fuels, oxidizers (replacing air), and water will be prohibitive. Thus the lunar ore refining operation will be dependent on the development of new concepts unless future engineering breakthroughs allow current terrestrial ore refining processes to become economical closed cycle processes.

Some four new concepts were considered in this study. They are fusion torch refining, electrochemical refining, vaporization refining and

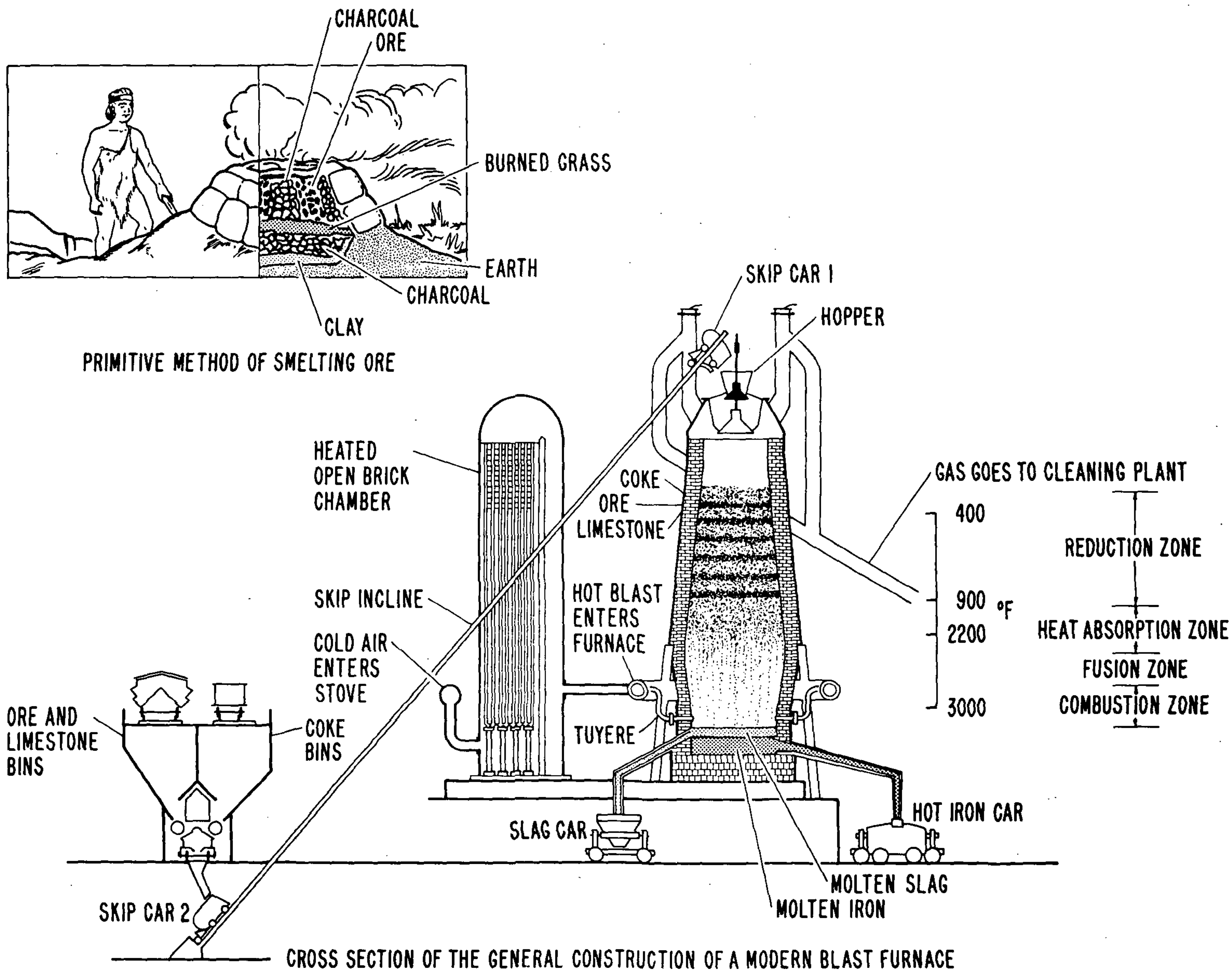

Figure 6. Historical Comparison of Ore Refining Methods.

differential melting refining. The analysis showed that the fusion torch was probably the most desirable of these concepts although it is the most technologically demanding and difficult. No attempt was made to determine the hardware requirements for these concepts because of the lack of data necessary to synthesize a design. Thus results for this particular part of the study are confined to the energy requirement and its cost. The fusion torch concept for mineral ore refining is described below, including its energy requirement and cost. The other three concepts are only briefly described since they require more energy and therefore are expected to be more costly than the fusion torch refining.

The fusion torch, shown schematically in figure 7a and b, is a theoretical concept configured for using the high temperature plasma of a controlled thermonuclear fusion reaction. The high temperature of the plasma (exceeding 50×10^{6}°C) will essentially vaporize and ionize any material that it comes in contact with. Once the lunar ore is vaporized and ionized it can be separated electrostatically, and the desired minerals neutralized, condensed and solidified. The concept is simple but the engineering of the working system will be challenging; e.g. a means of controlling the high temperature plasma must be found. Currently the standard method of confining high temperature plasmas is through intense magnetic fields. But this requires heavy magnets which will add appreciably to the cost of transporting the device to the moon and is thus undesirable.

But the use of the fusion torch for refining lunar minerals would result in minimal energy cost since the direct use of the fusion plasma bypasses the conversion losses in converting thermal energy to electrical energy or other energy form. For the nominal production rate of 4.5×10^{6} kilograms per year of pure mineral (and assuming the mineral dressing has already concentrated the 1 percent ore to 25 percent), the energy cost would nominally be about $2 million ($200 \times 10^{6}$ kilowatt-hours per year).

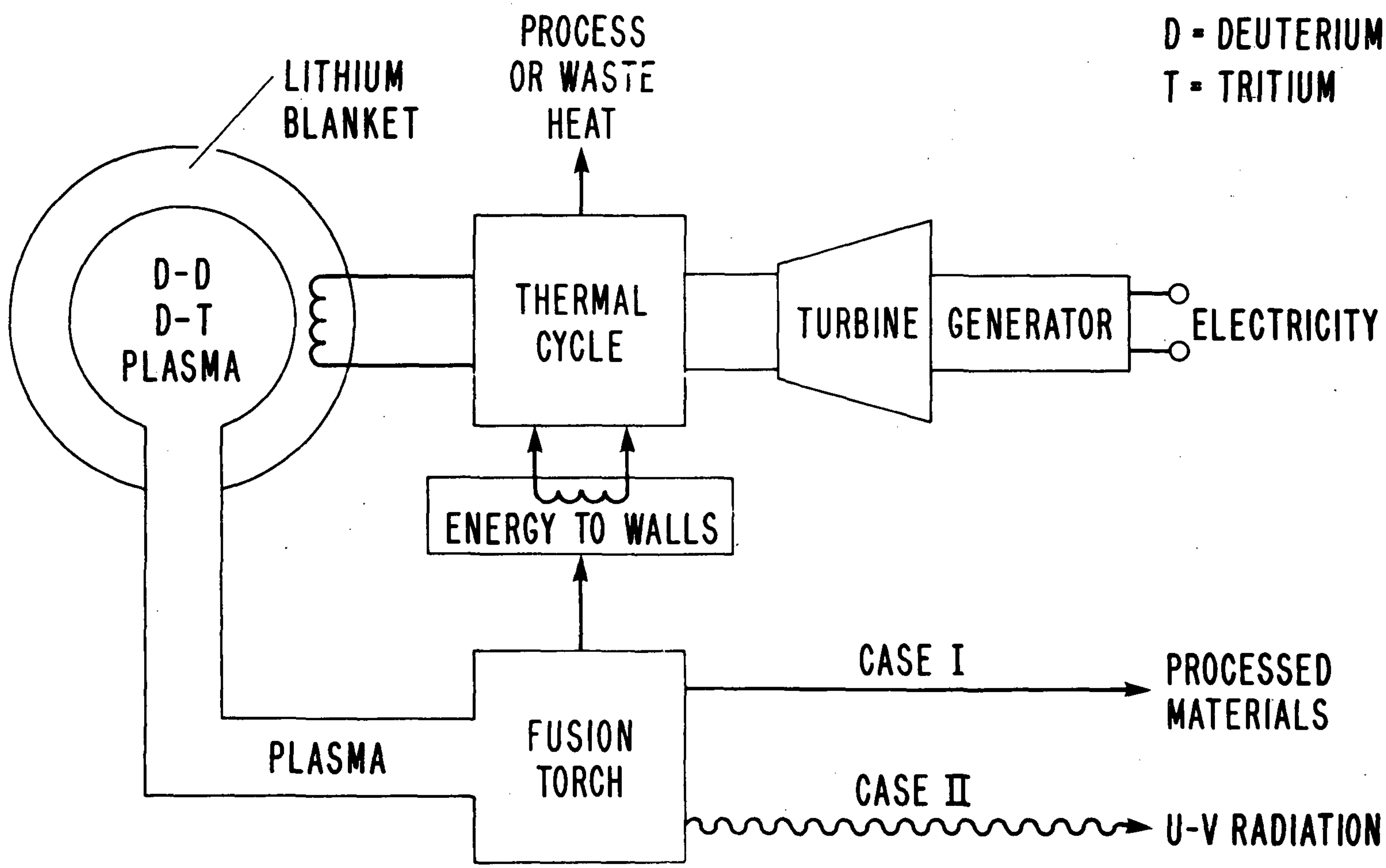

Figure 7a. Energy Conversion with Fusion Torch D-D & D-T Fuel Cycles.

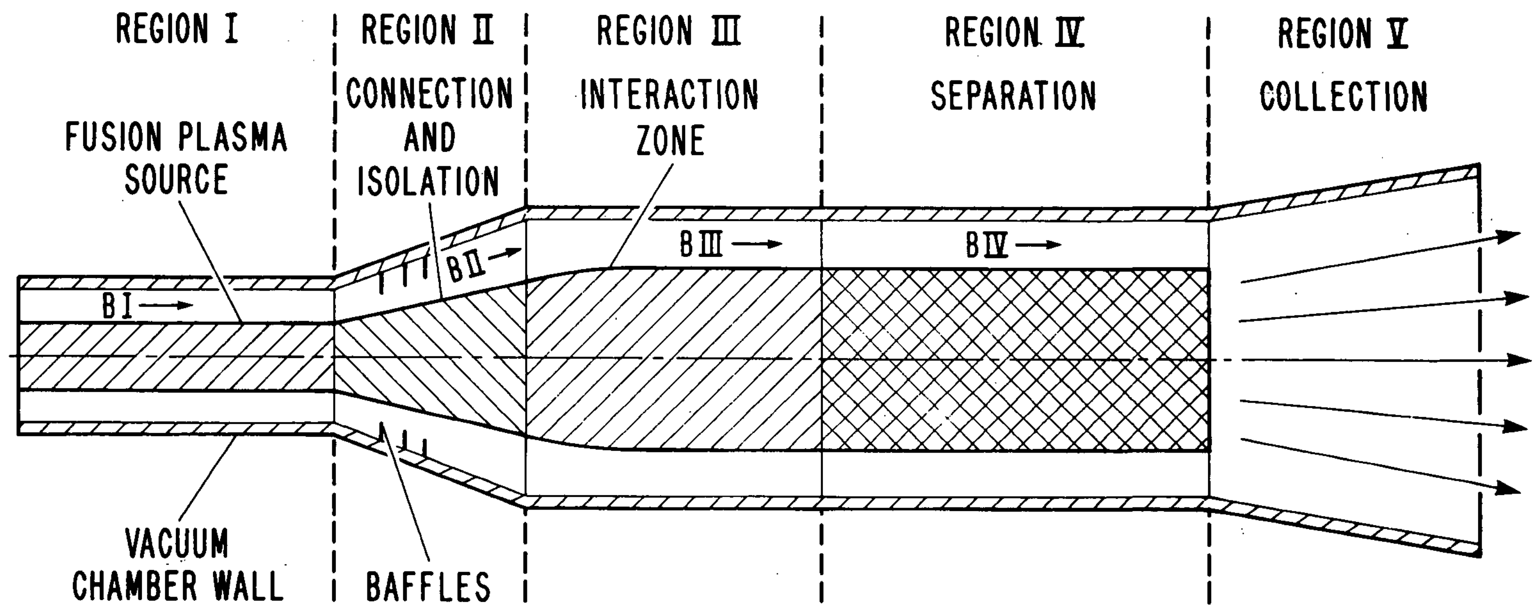

Figure 7b. The Fusion Torch.

Each of the other three concepts examined in the study are described briefly below:

1) Electrochemical refining is the name used here for the refining process using an electrical or magnetic field to separate the constituents of the ore in the molten state. This process was configured on work being conducted on migration of metallic ions in solids under the influence of electrical fields by Professor Luth at Stanford.

2) Vaporization refining is a concept utilizing the differences in the vaporization temperatures of materials to effect the separation. The high temperatures and heat required with this process along with the need of some reducing atmosphere for oxide reduction leads us to conclude that the fusion torch would be more desirable.

3) Differential melting refining is a relatively crude refining process for separating the mineral ore by using the different melting points of its mineral components. This concept will work for particular types of ores only and thus its applicability is limited.

Of all the processes discussed here, only the fusion torch is a continuous process; all the others are batch processes. Batch processes are inherently less efficient and generally require larger facilities to provide equivalent production capabilities as compared to a continuous process. Thus the facility requirements for the batch processing concepts are expected to be greater. The process energy requirements for the batch processes were estimated in the study and they were higher than the fusion torch concept. Further studies to obtain equipment requirements and costs are necessary before final comparisons between concepts can be made. But it is relatively clear that the fusion torch would ultimately be the preferred choice.

Mineral Dressing and Refining Cost Sensitivity. - The cost of processing the mined ore includes the overall costs of dressing the ore and refining the ore into the basic mineral. Cost breakdowns of the operations, based on mineral content, are presented in table 6.

TABLE 6. - MINERAL DRESSING AND REFINING COSTS--
DOLLARS PER KILOGRAM OF REFINED MINERAL

Percent Mineral Content	Mineral Dressing (Dollars per Kilogram)	Refining (Dollars per Kilogram)
1	40. - 350.	8. - 28.
25	1.70 - 13.	.30 - 1.00
50	.80 - 6.50	.15 - .50
75	.50 - 4.50	.10 - .40
100	.40 - 3.50	0

The costs from these two primary processing steps are not directly additive. That is, the mineral dressing operation generally concentrates the ore to about 90 percent (or even higher) but the basic mineral (aluminum, copper, iron, etc.) content in the concentrated ore is dependent on the elemental makeup of the ore. For example, 100 percent aluminum ore (Al_2O_3) is 53 percent aluminum metal by weight while 100 percent iron ore (Fe_2O_3) is 70 percent metallic iron by weight. Therefore, the refining process cost to be added to the cost of mineral dressing (for whatever mineral content) for the example aluminum ore would be those shown for the 50 percent row in table 6 and the cost for iron ore would be close to those shown for the 75 percent row.

A bound on the mineral dressing and refining cost will range from a minimum of $0.40 to a high of $400 per kilogram of refined mineral. If lunar ores similar in richness to terrestrial ores are mined, then the nominal processing cost will be on the order of $2.00 per kilogram of refined mineral. An optimistic cost for the processing operations of $0.15 per kilogram ($0.07 per pound) of refined minerals can be concluded if it is assumed that ores with 50 percent mineral content can be found and negligible mineral dressing is required prior to refining by the fusion torch.

As seen, there is a wide range in the mineral cost depending on the mineral content of the ore being refined, its ore form, and the processing technology that is assumed.

Lunar Surface Payload Launcher

A transportation system based on chemical and nuclear space vehicles for bringing lunar ore back to Earth would be too costly. If the system were similar to the one used to transport supplies from the Earth to the moon (discussed earlier), the fuel costs would add approximately $550 to the cost of each kilogram of mineral delivered to Earth. Thus a new transportation concept, minimally dependent on Earth resupply must be used. The electromagnetic accelerator is a concept that may meet the preceding requirement. The electromagnetic accelerator operates on the basis of the force generated between opposing magnetic fields.

A conceptual design of an electromagnetic accelerator for delivering lunar minerals to Earth was made for this study. The system is composed of the stationary coil (which includes the track), moving coil and the control room. A sketch of the stationary coil and moving coil arrangement is shown in figure 8. The moving coil accelerates down the inside of the stationary coil until the desired velocity is reached, at which point the payload and moving coil separate and the moving coil is decelerated. The end section of the stationary coil (beyond the point of separation between the moving coil and payload) will be designed with the required curvature to compensate for the gravity turn in the payload trajectory.

Payload related design parameters requiring consideration in sizing the accelerator are the required final velocity, acceleration limit, and total payload weight to be handled per year. The final velocity desired at the end of acceleration is 2900 meters per second. Acceleration length (track length) required to achieve this velocity is dependent on the acceleration level; a 10 g (Earth "g") constant acceleration limit results in a 40 kilometer track length. Total payload to be handled by the

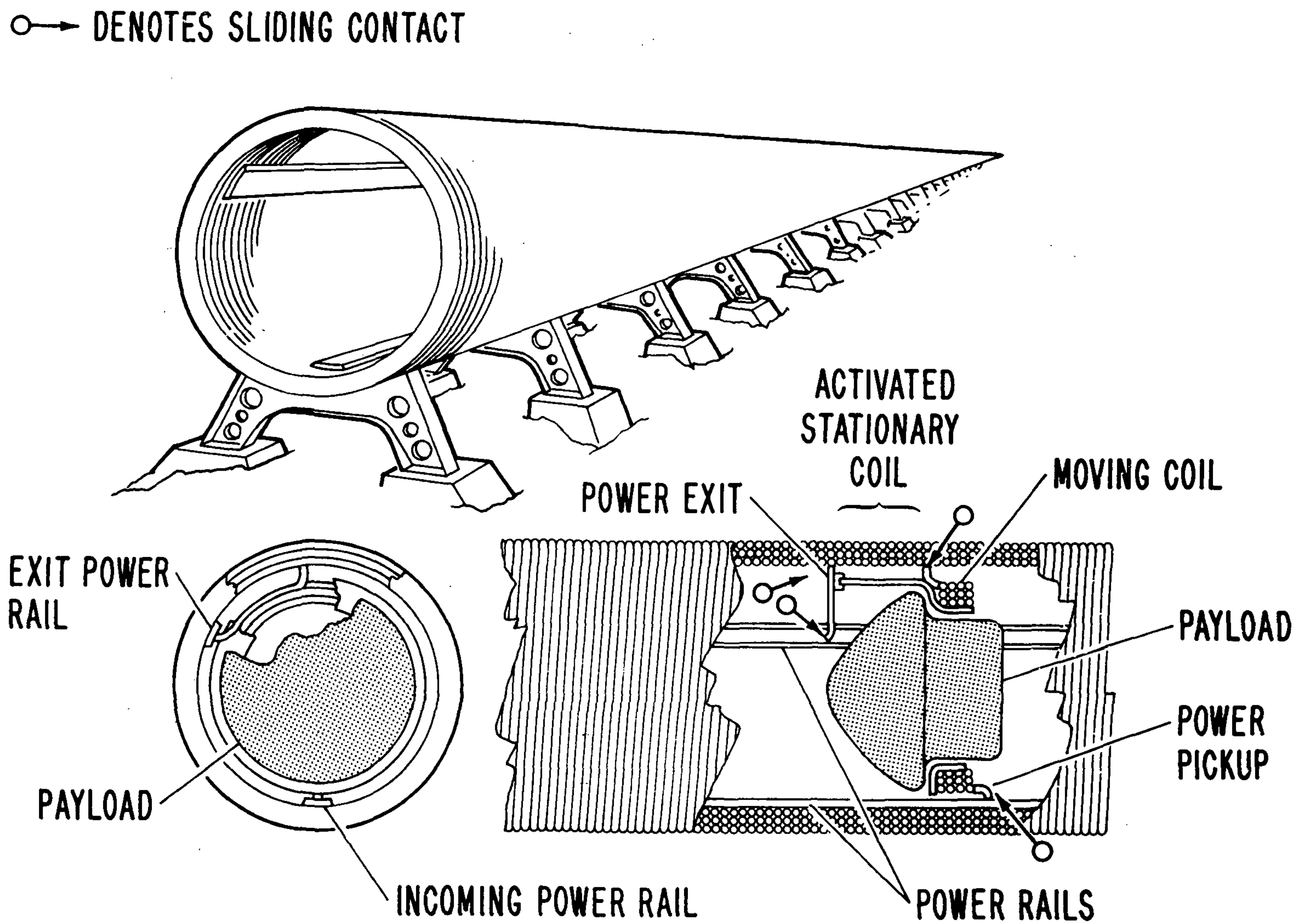

Figure 8. Sliding Coil Electromagnetic Launch Device for Lunar Payloads.

The overall electromagnetic accelerator system using non-superconducting coils, sized for a payload return capability of 4.5 x 10^6 kilograms per year and launch rate of one per day, will weigh about 70 x 10^6 kilograms and cost about $40 billion. The payload size per launch is about 14,000 kilograms. If a 20-year lifetime is assumed for the system, the payload delivery cost is about $450 per kilogram. Payload delivery cost is directly related to the frequency of launch and payload size with the payload size dictating the size of the accelerator; the larger the facility the higher its cost.

If higher acceleration and/or more frequent launches are acceptable, and if superconductivity and improved structural materials technology become available, the transport costs are expected to drop to as low as $4.50 per kilogram. In all probability some cost approaching this lower cost should be attainable assuming that R&D funding in this area continue in the future.

LUNAR MINERAL COST

Total Cost of Lunar Minerals Delivered to Earth

The Earth delivered cost of lunar minerals depends on many parameters, ranging from the environment to the kinds of technologies available for transporting systems and for conducting the mining and refining operations. The influence of these parameters on the cost is covered earlier in this report. Note that some of the parameters influence the mineral cost directly while others do so indirectly. For example, the transportation cost to the moon influences the mineral cost indirectly by effectively increasing the cost of equipment and support for the mineral mining and refining operations. On the other hand, the cost of transportation for bringing the minerals back to Earth has a direct influence on the mineral cost; it adds directly along with the mineral mining and refining costs to the overall cost.

The Earth delivered cost of lunar minerals versus mineral content of ore for the nominal refined mineral production rate of 4.5 x 10^6 kilograms

(10^7 pounds) per year is shown in table 7. As seen in table 7, uncertainties in the total cost are dominated primarily by return transportation costs. However, at low ore richness, uncertainties in mineral dressing and refining costs also have a large impact on the total cost.

Cost Comparison of Terrestrial and Earth Delivered Lunar Minerals

The reasons for seeking lunar minerals have been elaborated earlier. In this section the mineral costs, (lunar and Earth), are compared to determine whether the lunar minerals are competitive or have a chance of being competitive.

The prices of minerals are primarily functions of the rates of usage and availability. If the present trend of increasing usage continues so that the mineral reserves continue to decline, the mineral prices can be expected to increase. Figure 9 shows the total world consumption of 30 select minerals classified under three broad categories labeled precious metals, critical minerals, and minerals common to Earth and moon. Usage rate curves for the year 1968 and 2000 are based on data presented in reference 23 and the curves for the year 2050 were obtained by extrapolating the data from the same reference. The specific materials that make up the three categories in this figure are noted on figure 10. Figure 10 shows the usage rate and cost for 30 commonly-used terrestrial metallic minerals. The consumption rate and cost shown are from data supplied in reference 23 with the exception of dotted portions of the curves. These dotted sections of the curves have been estimated based on relations between cost, usage, and availability of minerals using procedures discussed in reference 23.

Cost comparisons of terrestrial and Earth delivered lunar minerals are shown in figure 11. Those minerals shown in the figure are for minerals relatively abundant on the moon and on the Earth. The terrestrial mineral costs have been spotted to correspond to the actual mineral content of the

TABLE 7. - EARTH DELIVERED COST OF LUNAR MINERALS[a]
(Dollars per Kilogram)

Cost Element	Percent Mineral Content				
	1%	25%	50%	75%	100%
Lunar Base[b]	8.50	8.00	7.00	6.50	6.00
Base and Crew Logistics	35.00	33.00	31.00	29.00	27.00
Mining[c]	60.00	2.50	1.00	1.00	0.50
Mineral Dressing and Refining[c]	50.00 - 400.00	2.00 - 15.00	1.00 - 7.00	0.50 - 5.00	0.40 - 3.50
Mineral Transport[b]	4.50 - 450.00	4.50 - 450.00	4.50 - 450.00	4.50 - 450.00	4.50 - 450.00
TOTAL COST	158.00 - 953.50	50.00 - 508.50	44.50 - 496.00	41.50 - 491.50	38.40 - 487.00

(a) Refined mineral production rate is 4.5×10^6 kilograms per year.
(b) Facilities lifetimes are assumed to be 30 years.
(c) Equipment lifetimes are assumed to be 10 years. (Earth launcher was based on 20 years.)

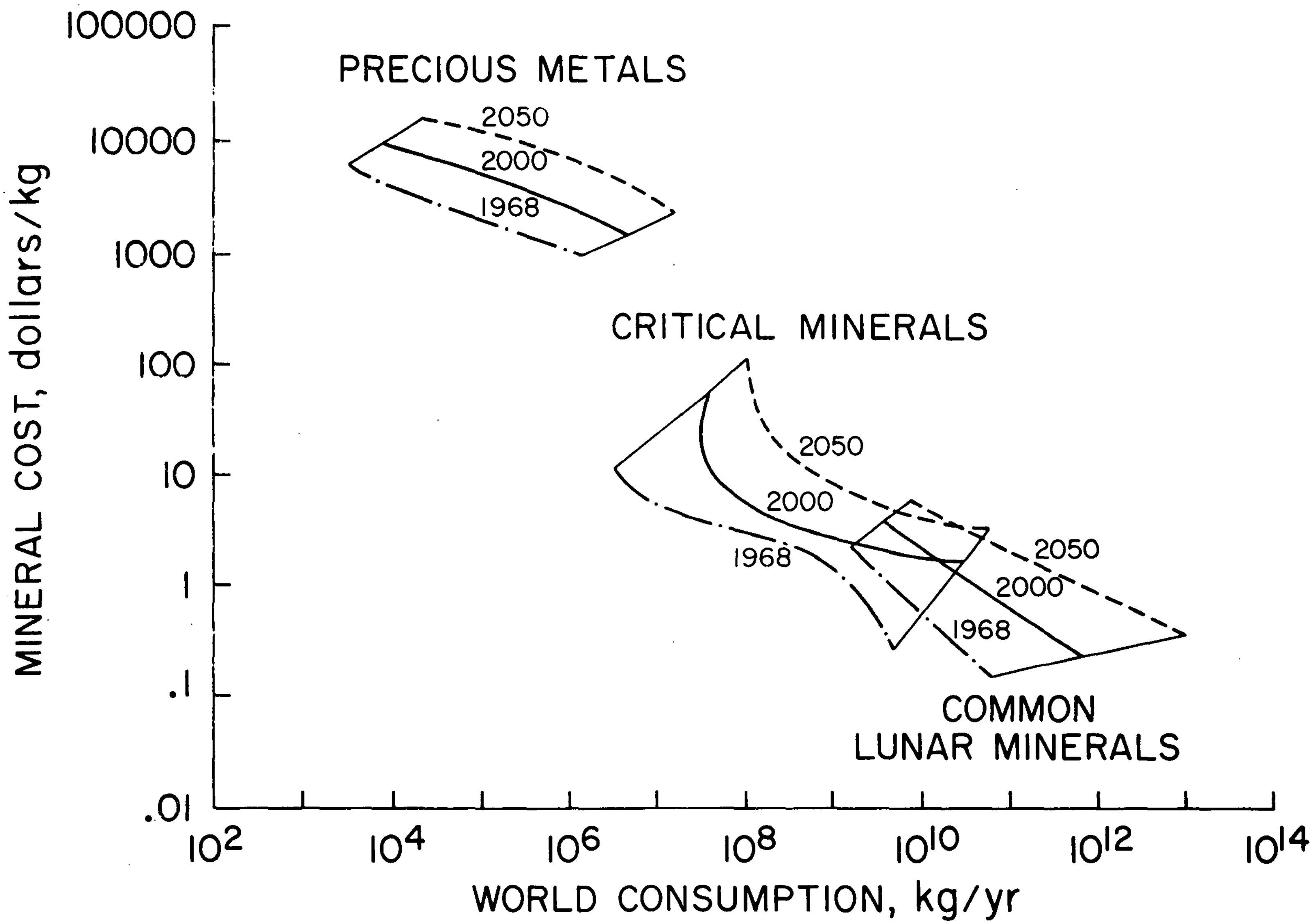

Figure 9. Total World Consumption Rate for Several Selected Minerals.

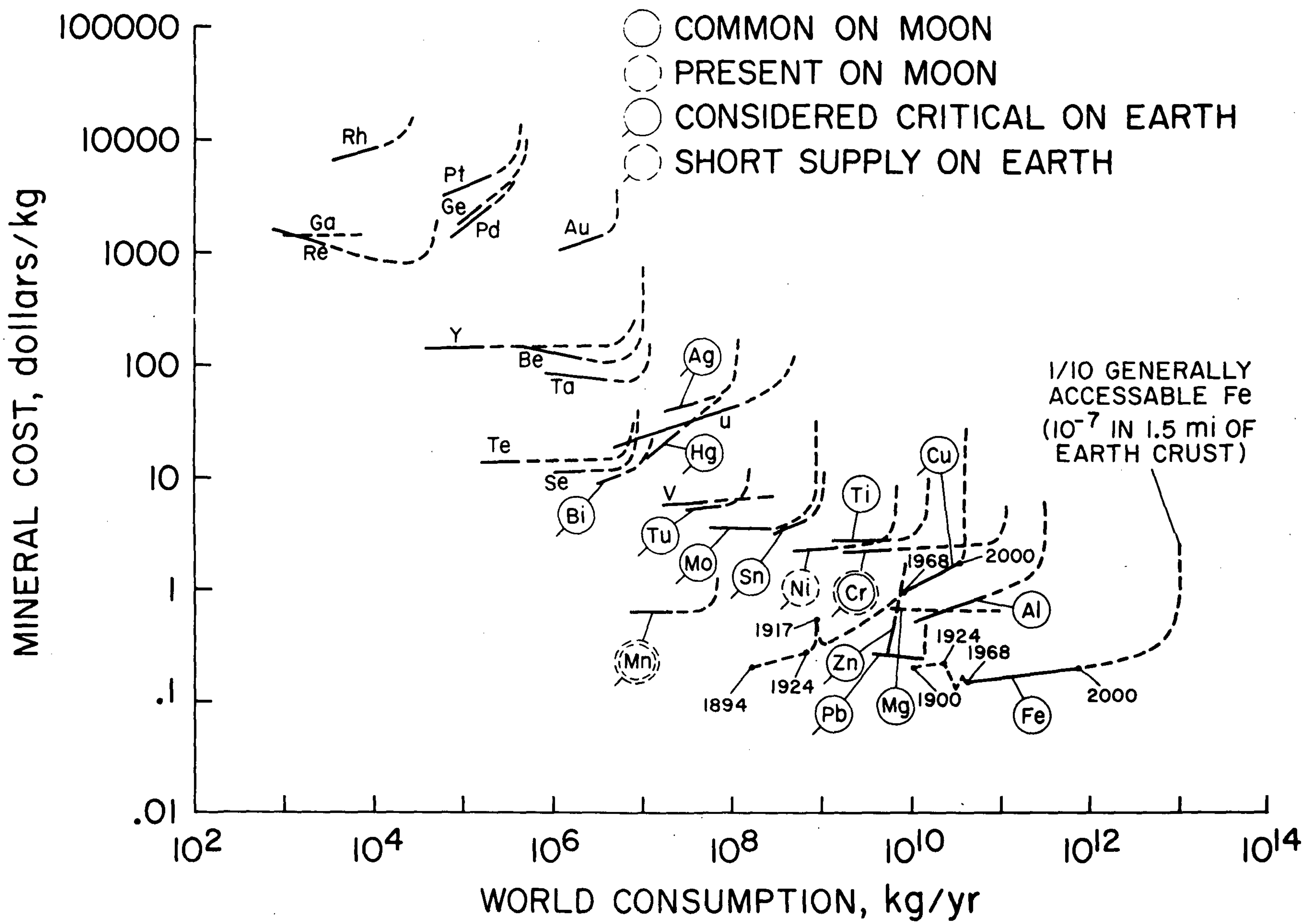

Figure 10. Total World Consumption Rate for Thirty Selected Minerals.

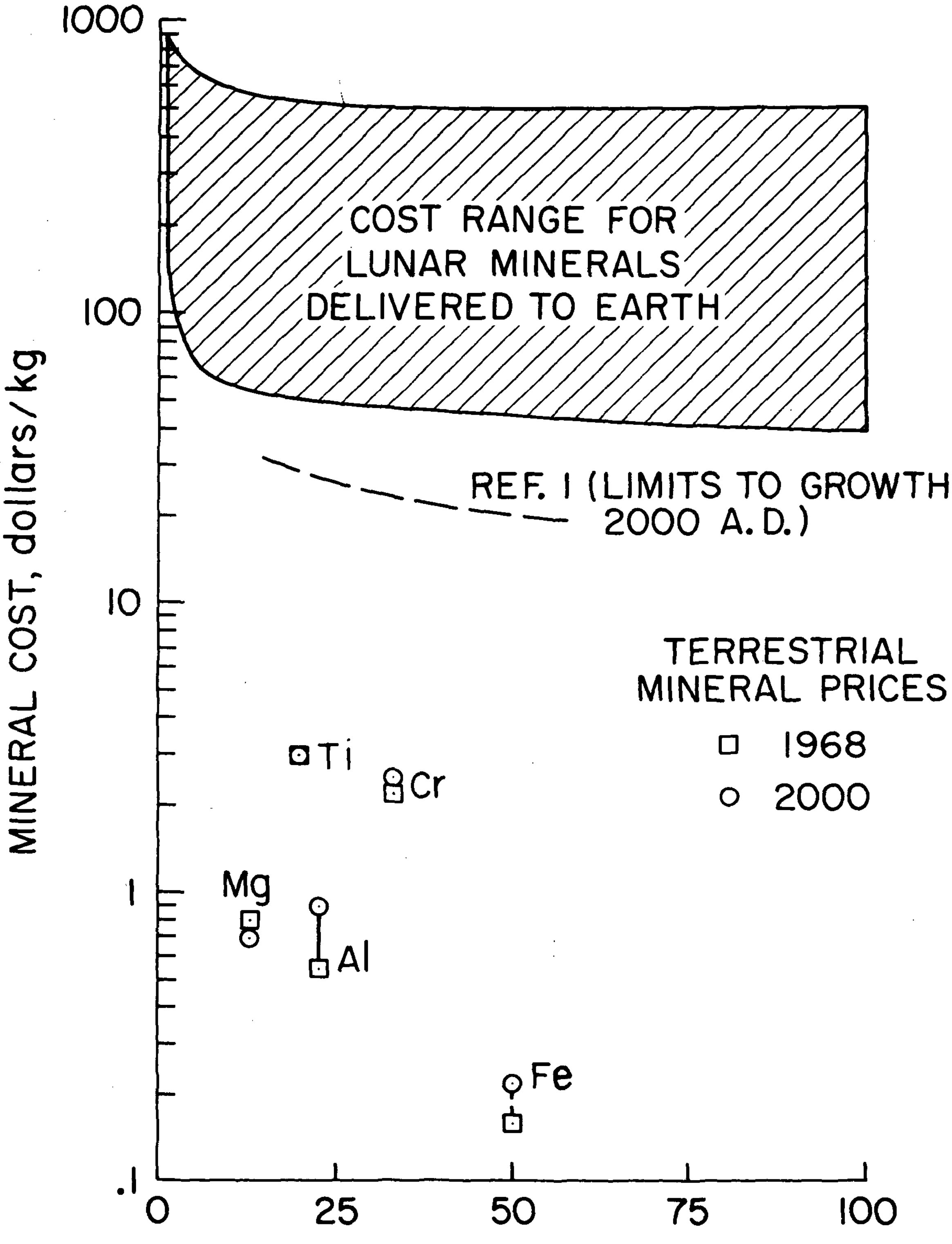

Figure 11. Lunar-Terrestrial Mineral Cost Comparison.

ores being mined currently. The range in cost* for these terrestrial minerals denotes the cost escalation that is expected between now and the year 2000 (except magnesium). Some degradation in ore grades is expected in that time period but no drastic effect on prices is predicted by the Bureau of Mines. This figure clearly shows the approximate two orders of magnitude higher cost of lunar minerals.** Greater cost differences occur if the more pessimistic values for lunar minerals are assumed.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The results indicate that lunar mining as a commercial enterprise for supplying minerals for terrestrial needs is not feasible by circa 2000 A.D. The cost of the lunar minerals is approximately two orders of magnitude higher than terrestrial minerals. However, other factors such as unforeseen technology breakthroughs which result in cost reduction of lunar mining, depletion of minerals, or increases in demand for raw materials which escalate terrestrial mineral prices can conceivably make lunar mining a commercially-feasible enterprise.

2. The concept of lunar mining purely on a technical basis seems to be feasible, but without certain technology breakthroughs, impractical. Much of the technology required for such an enterprise ranging from the design, construction, transport, and enplacement of the base to remote controlled

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* Although the terrestrial mineral prices are those predicted for circa 2000 A.D., they unfortunately do not reflect the true availability picture for these minerals. Past experience with availability and price of materials indicates that the price generally lags behind the material availability (depletion) curve.

** The cost projection in reference 1 shows an order of magnitude increase in terrestrial mineral costs in the time period of this study. Based on these results, the cost difference between lunar (the lower curve) and terrestrial minerals narrows to less than half an order of magnitude for some minerals.

mining machines is already at hand. Some engineering breakthroughs, particularly in the refining process, would be helpful; that is, the refining process should be made independent of its current requirements for abundant air and water.

3. Pivotal technology areas for lunar mineral exploitation are the mineral refining process and the transportation system for bringing the mineral from the moon to the Earth. These two areas have the greatest impact on the cost of lunar minerals. Either the assumption of available fusion power and torch must be correct or engineering breakthroughs must occur. Otherwise the logistic requirements for mineral refining will be overwhelming. And without engineering development of a low resistance coil (super conducting) with low sliding friction at the contact points, the mineral transportation system configures in this study will not be feasible and transportation costs will be prohibitive.

These conclusions may not be valid for cases other than where the lunar ore is mined and refined for return to Earth for consumption. For example, mining of lunar minerals in support of lunar operations may be a feasible undertaking. (Also see ref. 2)

Recommendations

Based on the results of this study, specific studies of the advanced technologies discussed in this report, tempered by the terrestrial mining and refining requirements, are recommended. These studies could be done in concert with the Bureau of Mines and should analyze, and, where feasible, subject these technology concepts to experimental verification. Technology items recommended for further study are:

1. Thermal Torch (Borer)
2. Electrolysis of molten basalt
3. Laser treating of rocks for breakage
4. Physical properties of mineral ores in vacuum
5. Separation of ionized materials (anticipation of an operational fusion torch).

Results from these studies could be useful in helping to reduce lunar mining costs. But of greater importance is that the results might be useful to terrestrial mineral mining and refining. For example, the preferred commercial ore for producing titanium metal is rutile and it is in short supply, while ilmenite, another titanium ore, is plentiful but more difficult to process and thus not used generally as a source of titanium metal. With the electrolysis method of refining, it may be possible to use the ilmenite ore to obtain metallic titanium economically. This need for new technology in terrestrial mining and refining is additionally illustrated in the following paragraph.

A large part of the terrestrial mineral problem, as indicated upon examination of publications by the Bureau of Mines, is that much of the high grade ore will be depleted soon (the year 2000-2050 A.D.) if consumption rates and new ore discoveries continue as projected. This will necessitate using lower grade ores. But these lower grade ores are more costly to process. Moreover, the mining operations require large volumes of soil to be moved which may have adverse impact on local ecology and thus be in conflict with environmental restrictions. Modifications to these operations, such as offered by melting the low grade ore in place by the thermal torch (borer) and refining it by electrolysis, will minimize any impact that the mining operation may have on the environment. Therefore, advanced technologies such as these are worthy considerations for future study.

Studies examining lunar mining and refining for the utilization of lunar mineral resources for other applications such as lunar facilities construction, manufacturing of spacecraft, and structural components for outer planet exploration may be desirable in the future if these undertakings become part of our goals in space. For those programs which require large quantities of goods on the moon, the high delivery costs may make the use of the lunar resources in facility construction, etc., more economical.

Final Comments

The results of this study indicate that lunar mining is not a commercially feasible enterprise when the mined products are destined for terrestrial use. Also, the availability of the technology required for lunar mining is marginal. Rather significant progress in power generation, mineral refining (Development of the Fusion Torch), and space transportation systems are required. It is expected that progress in these areas will occur because of our concern for terrestrial needs as evidenced by the public awareness and concern over the current energy crisis and depletion of resources. As new technologies come to fruition as we attempt to solve these terrestrial problems, the time will come when a re-examination of lunar mining will be warranted.

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